A Real-time TFT Compensation through Power Line Current Sensing for High-resolution AMOLED Displays

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Abstract
A real-time compensation method for TFT variation is proposed for AMOLED displays. This method enables a column driver to sense TFT current of each pixel using a power line as a current sensing line while driving a pixel without increasing a scan time. A fast OLED degradation sensing is also possible to compensate the image sticking problem. A target application of the proposed driver is a simultaneous emission full-HD AMOLED TV, whose scan time is 7.5 ms at a scan frequency of 120 Hz.

1. Introduction
AMOLED display is currently being a strong candidate for a high-quality TV market because of its fast response time, wide viewing angle and high contrast ratio. A high-resolution TV requires a fast driving speed of a column driver IC, which makes most of AMOLED displays in the market rely on a voltage-driving scheme. However, temporal and spatial TFT variation causes image degradation. The threshold voltage ($V_{TH}$) compensation in pixel circuits, a solution for this problem, reduces an aperture ratio due to additional TFTs and capacitors. Although current driving schemes have been proposed for an accurate driving, their slow driving speed is not appropriate to a high-quality TV market because of its fast response time, wide viewing angle and high contrast ratio. Another issue of the AMOLED display is the image sticking problem due to the finite lifetime of an OLED. One of the solutions for the problem is to sense the luminescence degradation of OLED electrically and compensate it for luminescence uniformity [4].

A proposed AMOLED driving system in Fig. 1 realizes an external TFT compensation in real-time through a power line current sensing scheme. The proposed column driver senses TFT variation while driving the large-size AMOLED display. In addition, it senses the current of the OLED at a constant anode voltage to measure the degradation before displaying, and the external system compensates the OLED degradation.

2. Power Line Current Sensing
TFT current of each pixel is highly affected by $V_{TH}$ variation rather than mobility variation. The main driving TFT in each pixel has a different $V_{TH}$, and constant current stress on the TFT can also shift the $V_{TH}$. This is why a real-time current sensing is necessary. To sense the $V_{TH}$-shift, a previous single bit correct the $V_{TH}$ variation ($\Delta V_{TH}$) has also been proposed [3]. However, this scheme requires an additional calibration time to measure TFT characteristics, such as the $V_{TH}$ and mobility.

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Figure 1. Concept of Proposed AMOLED Driving System

Figure 2. Power Line Current Sensing Scheme
are 8-bit current data. These data are transformed to voltage data by a gamma look-up table (LUT) and also directly sent to the column driver IC. The current DAC (CDAC) in the driver converts the current data to the data current (\(I_{\text{DATA}}\)), which is compared with the TFT current (\(I_{\text{SENSE}}\)). The transformed voltage data are corrected by a \(\Delta V_{\text{TH}}\) compensation block and sent to the column driver IC. The voltage DAC (VDAC) with the voltage buffer drives pixels according to these data.

The \(I_{\text{SENSE}}\) sensed through the power line is compared with the \(I_{\text{DATA}}\) by the current comparator. Assuming that the mobility among pixels is not significantly different, the difference between the \(I_{\text{SENSE}}\) and the \(I_{\text{DATA}}\) mainly comes from the \(\Delta V_{\text{TH}}\) among pixels. The gamma LUT contains a relationship between \(V_{\text{DATA}}\) and \(I_{\text{DATA}}\) like the reference \(I\)-V curve in Fig. 4. This curve is based on the \(V_{\text{TH}}\) and mobility of the reference TFT. Thus, the current comparator output (CMP) implies whether the \(V_{\text{TH}}\) of the TFT in each pixel is larger than that of the reference TFT or not. If the \(I_{\text{SENSE}}\) is larger than the \(I_{\text{DATA}}\) (CMP=1), the \(V_{\text{TH}}\) of the TFT is smaller than the reference \(V_{\text{TH}}\). If smaller (CMP=0), the \(V_{\text{TH}}\) of the TFT is larger than the reference one. The CMP is sent to the \(\Delta V_{\text{TH}}\) compensation block and corrects the \(V_{\text{TH}}\) of each pixel by one bit. The corrected \(\Delta V_{\text{TH}}\) of each pixel is stored in memory. The correction is continued until the CMP changes, which means that the \(\Delta V_{\text{TH}}\) is finally corrected. However, since the constant current stress on the TFT shifts the \(V_{\text{TH}}\) while displaying, the correction should be repeated every certain period. This time period is determined by the stability of the TFT.

Memory only stores the corrected \(\Delta V_{\text{TH}}\) information per pixel. If the \(\Delta V_{\text{TH}}\) is a 5-bit, 4Mbyte memory is enough to correct the TFT variation of the full-HD AMOLED display.

4. Circuit Implementation

Fig. 5(a) shows the detailed circuit implementation of the column driver. Digital components receive a clock signal and serial voltage and current data. Voltage driving is performed by a 10-bit VDAC and a class-AB voltage buffer. The current sensing scheme is comprised of a current follower, a CDAC, a current S/H and a latched comparator.

Fig. 5(b) shows its operation. During the programming period when the power line is connected to the current sensing scheme, the \(I_{\text{SENSE}}\) flows from the current follower to the pixel because the follower has a low input impedance. To compare the \(I_{\text{SENSE}}\) with the \(I_{\text{DATA}}\), the difference between the two currents is directly integrated to the capacitor \(C_{\text{INT}}\) at the node \(V_c\) after the \(I_{\text{SENSE}}\) is settled. After the integration, the node \(V_c\) and the reference voltage \(V_{\text{REF}}\) are compared by the comparator. For exact determination, the comparator is offset-compensated [6]. The integration time \(t_{\text{int}}\) is the last 1\(\mu\)s of 1-H time.

If the \(I_{\text{SENSE}}\) is very small, the transconductance \(g_{\text{m1}}\) of the source follower \((M_1)\) can be lower with increased input impedance. A constant bias current \(I_{\text{BIAS}}\) to the follower can solve the problem by limiting the maximum input impedance. However, since this \(I_{\text{BIAS}}\) is also integrated at the \(V_c\), the current S/H should sample this current during the first scan time of a frame (CS=1) and hold it during the programming period (CS=0) to cancel the \(I_{\text{BIAS}}\).
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Figure 5. Detailed Circuit and Operation of the Proposed Column Driver

The 8-bit bit-inversion cascaded-dividing current DAC (BI-CCDAC) is employed to generate the data current [7]. The bit-inversion algorithm of the BI-CCDAC makes its INL curve continuous. The BI-CCDAC also generates two symmetric INL profiles by toggling an INV signal which changes the whole current paths. Therefore, a good linearity of the current DAC can be achieved by averaging these two symmetric INL curves. In the proposed scheme, averaging is realized by inverting the INV signal at the middle of the current integration time (INT=0). For the current uniformity among channels, the reference current calibration scheme in [7] is also employed.

5. OLED Degradation Sensing

To compensate the OLED luminance degradation, relationship between anode voltage and current for each OLED is needed. Also, the sensing operation should be fast because it is performed when the display device is turned on. In terms of the sensing speed, applying a constant reference current to the OLED and measuring the increment of an anode voltage requires a long sensing time because it is based on the current driving [3]. Meanwhile, applying the test voltage to the anode of OLEDs and measuring the OLED current enables a fast sensing because it is based on the voltage driving.

In the proposed power line current sensing scheme, the current follower directly applies the test voltage ($V_{TEST}$) to the anode of OLED through the power line by using the main driving TFT ($T_2$) as a switch. Fig. 6 shows the OLED degradation sensing and compensation through the power line. At the reset phase, the ELVSS is connected to the gate of all $T_2$ through $T_1$ to use the $T_2$ as a switch, and the current follower applies the $V_{TEST}$ to the power line. And then, the sensing switches ($T_1$) are sequentially turned on from the first row so that the current sensing scheme in the column driver senses the OLED current ($I_{OLED}$) when the anode voltage is the $V_{TEST}$. A successive approximation is employed for analog-to-digital conversion of the $I_{OLED}$. Since the current sensing scheme has a fast sensing capability, 15μs per a row is enough to settle the $I_{OLED}$ and convert it to the digital code. Thus, this can be done during a short time before displaying.

It is reported that the OLED luminance degradation ($\alpha=AL/A$) has a correlation with ($I_{OLED} - I_{OLED, init}$) / $I_{OLED, init}$, where the $I_{OLED, init}$ is the initial OLED current according to the anode voltage of $V_{TEST}$ [8]. This is measured at the factory setting. Thus, the OLED degradation compensation block computes the $\alpha$ for each pixel and stores it in memory. While driving, the block modifies the input display data according to the stored $\alpha$ value.

6. Simulation Results

The analog block of the power line current sensing scheme was designed and simulated in 0.18μm 20V HVMOS technology. The target application is defined as a 55" full-HD (1920x1080) AMOLED panel, which has a 1-H time of 7.5μs. The simulated panel loads are 10kΩ and 150pF for the data line and 3kΩ and 450pF for the power line, respectively. These loads are modeled by five equivalent resistors and capacitors.

Fig. 7 plots the transient response of the sensed pixel current ($I_{SENSE}$) at the current sensing block. It clearly shows that the $I_{SENSE}$ is accurately settled in a 1-H time and is compared with the $I_{DATA}$. At the $V_C$ node, the difference of the two currents ($\Delta$) is integrated and compared. At the first current sensing time ($I_{DATA}=84.71nA$), 11.31nA of the current difference, which is one-fourth of an LSB of the 8-bit CDAC, is integrated to 14mV of the integration voltage ($\Delta V_C$) and compared well by the offset-compensated comparator. The power line current sensing scheme can quickly and accurately sense the pixel current.

The simulated TFT current of a pixel at a single gray scale (001001101) according to the $\Delta V_{TH}$ is plotted in Fig. 8. This
gray scale is converted to 3μA by the CDAC. The TFT is emulated by a long-length MOSFET and the ∆V_{TH} is realized by changing the body voltage of the MOSFET. When the ∆V_{TH} is varying from -0.8V to 0.7V, the TFT current varies by at most 906nA from the reference current without the ∆V_{TH} compensation. However, after the ∆V_{TH} compensation, maximum current variation is reduced by 40nA. The error is due to limited resolution of both the VDAC and current comparator.

![Figure 7. Simulated Transient Response of Proposed Column Driver](image)

![Figure 8. Compensated and uncompensated TFT current at single gray scale (001001101) according to V_{TH} variation](image)

**Table 1. Performance Summary**

<table>
<thead>
<tr>
<th>Process</th>
<th>0.18μm 20V HVMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target application</td>
<td>55&quot; Full-HD (1920x1080)</td>
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<tr>
<td>1-H time</td>
<td>7.5μs</td>
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<tr>
<td>Panel load</td>
<td>Data line: 10kΩ, 150pF Power line: 3kΩ, 450pF</td>
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<tr>
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<tr>
<td>Data current range</td>
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<tr>
<td>OLED degradation sensing</td>
<td>15μs / row</td>
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7. Conclusion

The proposed real-time TFT compensation scheme drives the display data as fast as the voltage driving, and simultaneously senses the pixel current to compensate the TFT variation. Through the power line current sensing, the proposed driving method does not require an additional sensing line and an additional sensing time. Therefore, it is suitable to large-size display which needs fast driving and pixel uniformity. The simulation results verify that the proposed scheme drives the data voltage and senses the pixel current in a 1-H time of 7.5μs for the full-HD 120Hz driving. In addition, by reusing the column driver circuit, the proposed system is able to sense the OLED degradation in 15μs per a row and compensate the image sticking problem. This helps the AMOLED display have a higher luminance uniformity.

8. Acknowledgements

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9. References


